The Interplay among Black Holes, Stars and ISM in Galactic Nuclei
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Stellar Populations in Active Galaxies

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Abstract. The role of stars and starbursts in AGN has been a recurring issue for nearly as long as AGN have been recognized as hosts of interesting phenomena. The heated "starburst *versus* monster" controversy of the 80's and 90's was gradually replaced by "starburst *plus* monster" studies, as observational work in the past decade has firmly established that accretion onto a super-massive black-hole and star-formation coexist in many galactic nuclei. Whereas the physical link between starbursts and AGN remains unclear, there remains no doubt that starbursts affect a number of properties traditionally associated to the AGN alone, such as the so called "featureless continuum", emission line ratios and luminosities. This contribution glosses over some of the techniques used to diagnose stellar populations in AGN, focusing on recent results and how this type of work can lead us well beyond what became known as the starburst-AGN connection.

1. Introduction

The subject of stellar populations in AGN has gone through a history of love and hate over the past 3 decades. Once upon the time, stars were essentially seen as that unavoidable junk which pollutes the optical spectra of AGN, particularly type 2s (Seyfert 2s, LINERs and their relatives). Accordingly, the methodology to deal with starlight in those days was philosophically the same used to deal with sky features or cosmic rays: *Get rid of it!* This was achieved by modeling the spectrum as a combination of an elliptical galaxy template plus a non-stellar featureless continuum (FC), yielding the "pure-AGN" spectrum as the residual (Koski 1978). Since this approach postulates that stars in AGN are all old and boring, it is not surprising that few AGNauts cared about stellar populations at all, so meetings like these would not have been possible at the time. This "Get Rid of It" era lasted up to the mid-80's.

In the late 80's and 90's things changed radically from a "stars-have-nothing-to-do-with-AGN" to the "stars = AGN" idea put forward by R. Terlevich and collaborators, whose starburst model for AGN replaced super-massive black-holes (SMBHs) by young stars and their remnants as the power-engine of active galaxies. Those of use which were around at the time remember (some with nostalgia) the fierce debates in meetings across the globe (eg, Taipei 1992, Puebla 1996). The conflicting observational evidence back then fueled the controversy. For instance, while the discovery of Seyfert 1-like SNe supported the model, rapid X-ray variability and relativistic Fe Kα line-profiles were better understood in the framework of the black-hole paradigm.

The starburst $\times$ monster battle gradually disappeared from the headlines as the existence of SMBHs became conclusively established in the past decade. The interest in stellar populations in AGN, however, survives to the present day, and for a very good reason: Evidence of the presence of young and intermediate age population around AGN is now as solid as that for the existence of SMBHs! Young ($t < 10^7$ yr) and "mature" (10^{8-9} yr) starbursts have been found all across the AGN family: quasars (Brotherton *et al.* 1999), radio galaxies (Wills *et al.* 2002), Seyfert 2s (Heckman *et al.* 1997) and LLAGN (Cid Fernandes *et al.* 2004; González-Delgado *et al.* 2004). This very volume

reports new developments on this so called "starburst-AGN connection", as in the contributions by Rafaela Morganti, Wil van Breugel, Rosa González Delgado and others. Indeed, the mere fact that the word "stars" figures alongside "black-holes" in the title of an IAU symposium is a testimony of this new reality.

Having said that, I must point out that we are still a long way away from understanding the physical link between star-formation and SMBHs in AGN. In fact, except for a few cases (see van Breugel's contribution) we are not even sure such a causal link exists at all, as the coexistence of these two phenomena could simply reflect the fact that both live on the same gas-based diet, a trivial possibility one must always bear in mind.

Notwithstanding this obligatory warning, we have learned a great deal from such studies. Instead of attempting a thorough and fair review of the progress in the field, which would be impossible due to lack of space and mainly talent, these few pages highlight some recent results which illustrate how the careful modeling of stellar populations in AGN provides valuable tools both for researchers interested in studying starburst-AGN connections and those more interested in getting rid of the starlight to inspect the AGN itself. The work cited below was carried out with several friends, including R. González Delgado, H. Schmitt, T. Heckman, L. Martins, Q. Gu, J. Melnick, the Terlevichs, D. Kunth, my students and, last but not least, our chair-woman T. Storchi-Bergmann, who taught me a lot and worked very hard to organize this great meeting.

2. The tools of the trade: Diagnosing stellar population in AGN

2.1. *Spectral features*

Stars leave numerous imprints in an AGN spectrum. These are more easily detected when the AGN is weak or hidden, which explains why most of the progress in this field has been achieved studying type 2 nuclei. An incomplete inventory of stellar features detected in AGN include the PCygni lines of CIV and SiIV in the UV (González Delgado *et al.* 1998), the WR bump at ~ 4650 Å, high order Balmer absorption lines (Storchi-Bergmann *et al.* 2000) , the CaII K, G-band and MgI absorptions in the optical, the CaII triplet (Terlevich, Díaz & Terlevich 1990) and Si and CO bands in the near-IR (Oliva *et al.* 1999). Star-related features are also found, such as a soft component in X-rays due to a starburst driven wind (Levenson, Weaver & Heckman 2001). Another example is the 3.3 μm PAH feature associated with starburst activity (Rodríguez-Ardila & Viegas 2003), which, unlike most other tracers, can be applied to type 1 AGN and thus help solving the old conundrum that starbursts seem to be less frequent in Seyfert 1s than in Seyfert 2s, in contradiction with the unification paradigm.

Some of these features are easily transformed into stellar population diagnostics, while others require more work. For instance, the mere detection of PCygni lines or the WR bump implies the presence of starbursts a few Myr old, and Balmer lines signal the presence of 0.1–1 Gyr populations. The CaII K line and the 4000 Å break, on the other hand, can be diluted either by young stars or by AGN-light (the "starburst-FC degeneracy"), so their interpretation is trickier. The Ca triplet and CO lines in the near-IR by themselves do not offer great diagnostic power, but can be used to infer the stellar kinematics and the M/L ratio (Oliva *et al.* 1999), a tool which is yet to be fully explored in AGN.

2.2. *The new generation of stellar population tools*

The release of high spectral resolution evolutionary synthesis models by Bruzual & Charlot last year provided a much awaited tool to study stellar populations in galaxies. As other groups, we have implemented this new library in a code which fits a galaxy spectrum decomposing it into $N_\star$ simple stellar populations of different ages and metallicities.

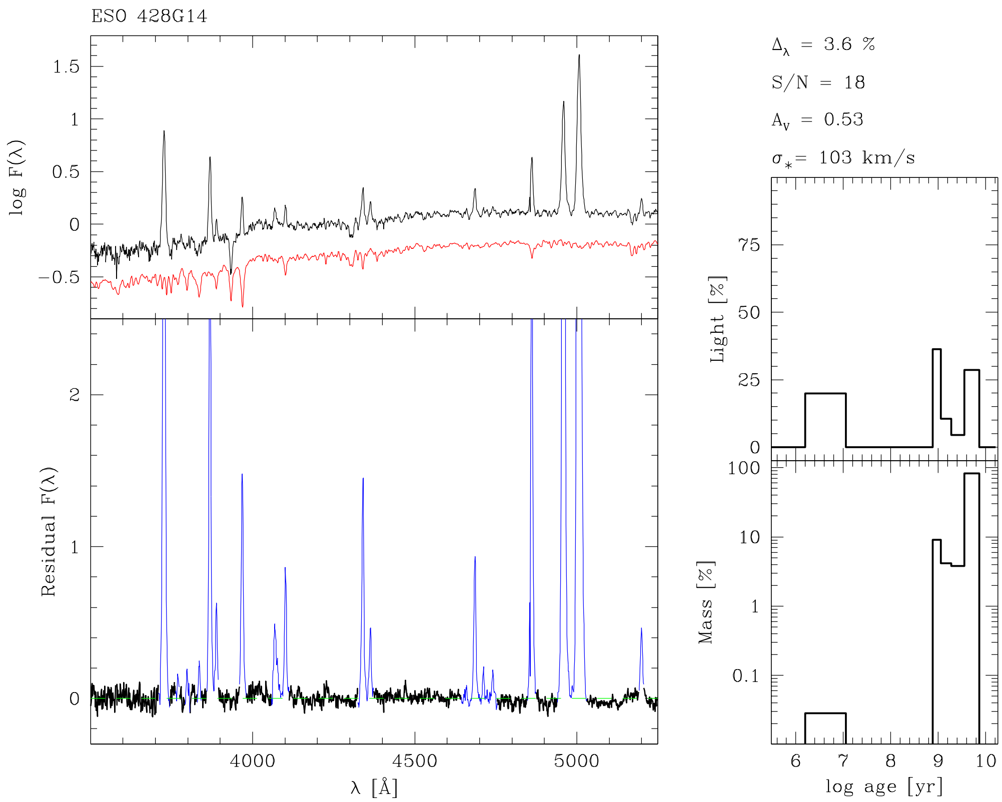

Figure 1. Example of the accurate spectral fits obtained with the new generation of stellar population synthesis models. *Left:* Observed, model and residual spectra. *Right:* Star-formation history, expressed as light and mass fractions versus age.

It so happened that at the time we were starting to analyze the stellar populations of a large and homogeneous sample of ~ 70 Seyfert 2s, which sounded like a good application for our code. The resulting spectral fits were incredibly good, as illustrated in Fig 1.

Fig 2 summarizes the properties of the central stellar populations of nearby Seyfert 2s. The left panel shows the population vector divided into "Young" (+ FC), "Intermediate age" and "Old" age-bins. The right plot expresses essentially the same information but in the more empirical $H_\delta \times D_n(4000)$ diagram. Seyfert 2s are scattered all over these diagrams, implying a wide variety of nuclear stellar population properties. At first sight this diversity seems to suggest no connection between their AGN and the stars around it. However, the $\sim 40\%$ frequency of $\lesssim 1$ Gyr populations in Seyfert 2s is high compared to galaxies of the same (early) Hubble type, and there are important connections between such starbursts and the AGN luminosity (Kauffman *et al.* 2003).

This new generation of stellar populations synthesis superseeds diagnostics based on individual spectral indices (§2.1), as modeling the full spectrum yields much better constrained fits and produces far more informative output information. Stellar masses, velocity dispersions (which gained added value in light of the $M_{\rm BH}$-$\sigma_\star$ relation which occupies several pages of this volume), extinction and the whole star-formation history of the system can be derived! As if this wasn't enough, to our surprise we are finding that even *stellar metallicities* can also be recovered within reasonable uncertainties. Applications

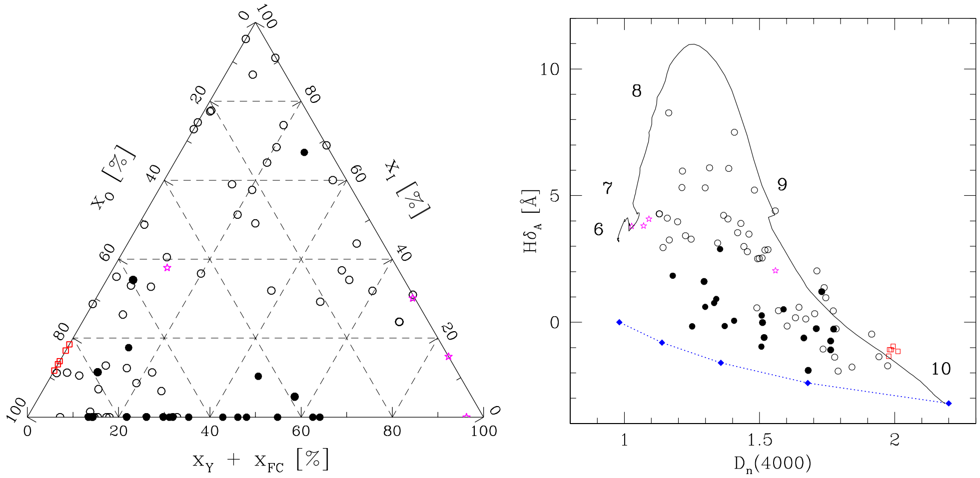

Figure 2. *Left:* Light fraction (at $\lambda = 4020$ Å) associated to Young stars plus an FC ($x_Y + x_{FC}$), Intermediate age (x_I) and Old populations (x_O). *Right:* $D_n(4000)$ versus Hδ_A diagram. The solid line shows the evolution of a BC03, $Z_\odot$ instantaneous burst, with numbers indicating ages of $10^{6\ldots10}$ yr. The dashed line represents a mixture of a $F_\nu \propto \nu^{-1.5}$ FC with a 10^{10} yr elliptical-galaxy-like stellar population. Circles represent the 65 Seyfert 2s in this sample; filled circles mark "Broad Line Seyfert 2s", in which scattered light is detected.

of such techniques to large AGN samples are starting to appear. Two important results of this kind of study are that AGN live almost exclusively within massive galaxies, and powerful AGN tend to have younger stellar populations (Kauffman *et al.* 2003). We have just started to play with SDSS galaxies, and, besides confirming Kauffman's results, we also find that AGN have metal rich stellar populations.

3. So What?

Given the lingering doubts about whether there is an actual physical connection between starbursts and AGN, I find it relevant to point out that modeling stellar populations in AGN has a lot to offer to those which don't care at all about stars, but, in the spirit of the "Get Rid of It" era, must deal with them. Here are a few why's.

3.1. *Stellar populations as clocks to measure AGN evolution*

A central goal of stellar population synthesis is to produce *age* estimates ($t_\star$). Knowing the ages of stars around AGN can give us major clues as to the evolution of AGN themselves! The idea is to age-date as many and as diverse AGN as we can and check whether their observed (luminosities, line-ratios, etc) and physical properties (M_{BH}, $\dot{M}_{BH}$) evolve, ie, if they correlate with $t_\star$. We are still in the first stages of this process, but one result is already clear from our studies of Starburst galaxies, Seyfert 2s, Transition Objects (TOs) and LINERs: On average,

$$\overline{t_\star}(\text{Starbursts}) < \overline{t_\star}(\text{Seyfert 2s}) < \overline{t_\star}(\text{Young TOs}) < \overline{t_\star}(\text{Old TOs}) = \overline{t_\star}(\text{LINERs})$$

where Young/Old refers to the presence of detectable of $\lesssim 1$ Gyr-old populations—as discussed by González Delgado elsewhere in this volume, Young LINERs don't seem to exist! Now, before jumping to interpretations recall that we are comparing apples and

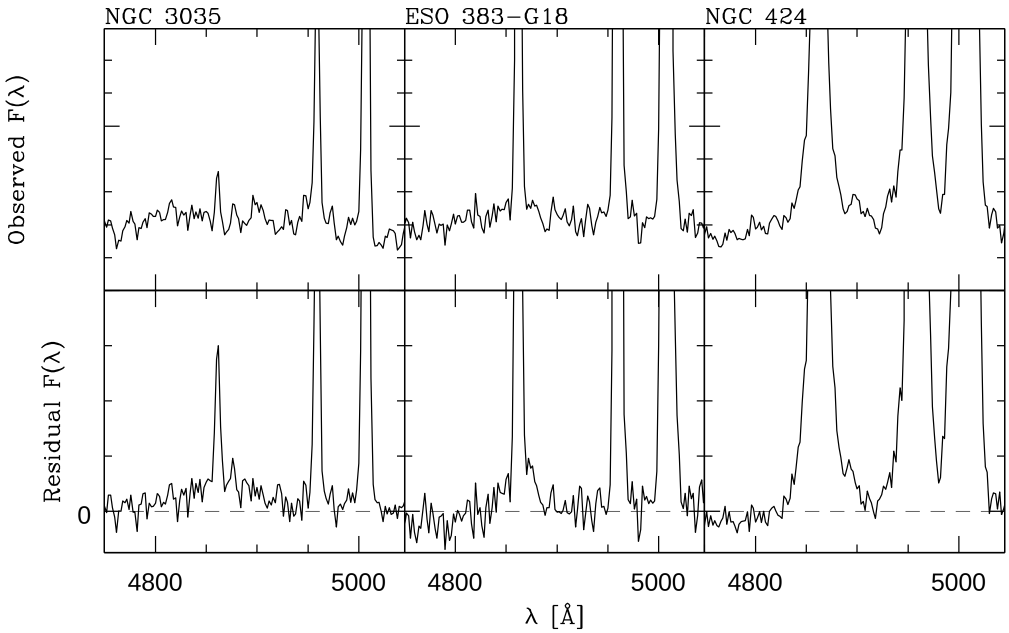

Figure 3. Top: Observed Hβ profiles in three Seyfert 2s. Bottom: Hβ profiles after subtracting the model spectrum, revealing a BLR-like component which we interpret as scattered light.

pineapples insofar as Hubble types are concerned. Seyferts and LINERs live in early types galaxies, Starbursts live in late types, with TOs split in between (Ho, Filippenko & Sargent 2003). The two plausible evolutionary sequences are thus: Seyfert 2 → Young TO → Old TO/LINER, and Starburst → Young TO → Old TO. While appealing, this is not really the whole story, since at least 30% of Seyfert 2s look just like Old TOs and LINERs in their stellar populations. Though much remains to be done, this seems a promising vein to explore, particularly in these days of mega-surveys.

3.2. *Detection of scattered light in Seyfert 2s*

Even the most starburst-AGN-connection-skeptic would agree that the elliptical galaxy + FC equation of the 70's and 80's is horribly wrong for many Seyfert 2s. One consequence of this template mismatch is that it often produced too strong an FC to be compatible with the unified model given absence of broad lines in Seyfert 2s and their low polarizations (Cid Fernandes & Terlevich 1995). This gave rise to the so called "FC2-problem" (Tran 1995). It is now clear that these 2nd (and dominant) FC component is originated in starbursts. Up to very recently the scattered Seyfert 1 component (called "FC1" by the pundits) seen via spectropolarimetry remained too weak to be detected in direct light.

This is no longer true. The new synthesis models do such a good job that we are now capable of spotting weak broad lines in the observed − model residual spectra, as shown in Fig 3. Our stars plus power-lawish FC spectral fits find significant FC strengths for most of these "Broad Line Seyfert 2s", as well as for objects where a hidden Seyfert 1 is known to exist from spectropolarimetry work (filled circles in Fig 2). The conclusion is obvious: We are detecting scattered light without a polarimeter! This is just an illustration of what population synthesis can do for you: The superb fits provided by these tools produce a clean "pure-AGN" spectrum, revealing weak features which would otherwise be hard to detect. This applies both to continuum and line emission.

3.3. *Dust and intermediate age stars in Low Luminosity AGN*

The third word in our meeting's title is ISM, of which dust is a part. Here too stellar population synthesis has a saying. For instance, in a spatially resolved analysis of LLAGN spectra, we have just found that Young TOs are much more reddened than either Old TOs or LINERs, and that this dust is concentrated in the nuclear regions. This dust could be due to star-forming regions, in analogy with what is found in starburst + Seyfert 2 composites, which tend to be dustier than Seyfert 2s whose inner stellar populations are predominantly old. However, no obvious signs of young ($< 10^7$ yr) starbursts are evident in most TOs, contrary to most expectations (eg, Shield's and Sarzi's talks). Alternatively, this dust could be associated to post-AGB stars, notorious dust-producers which have the right Gyr-scale age-range to match the observed spectra and whose ionizing radiation is also capable of producing TO-like emission lines (Binette *et al.* 1994).

4. Final remarks

I hope these pages have conveyed the idea that we have learned (the hard way, as usual) that the issue is not stars *or* monsters, but stars *and* monsters, and specially that the stellar content within the vicinity of the monster contains useful information for AGN studies. Historical difficulties in retrieving this information from data are quickly being overcome by a new generation of powerful stellar population synthesis tools, whose application to data of ever increasing quantity and quality is doomed to shed new light into our understanding of these fascinating objects.

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